PROGRESS REPORT FOR THE DOE/ARM PROJECT TITLED
Representation of the Microphysical and Radiative Properties of Ice Clouds in SCMs and GCMs

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This report for the Department of Energy's Atmospheric and Radiation Measurement (ARM) Program covers the period 1 May 2000 to 7 July 2000 for the grant DE-FG03-00ER62935, which is about the first 2 months of the project. Although officially this is a new project, some of the work scheduled for this project represents a continuation of effort from the previous project. This effort, the parameterization of size spectra for mid-latitude and tropical ice clouds, was not formally part of the previous project, but developed into a principal effort for this project. For this effort and others, there is no clear boundary between activities between projects. Nonetheless, we will try to distinguish progress made during this project vs. progress from the previous project.

1. Scientific Goals

This project contains three primary tasks: (1) continued testing of the ice cloud radiation scheme; (2) parameterizing bimodal ice particle size spectra for GCMs; and (3) determining ice mass sedimentation rates from ice clouds. In addition, many collaborative activities involving other institutions are included. We plan to retain all objectives described under (2) and (3) above, but reduce the effort for (1). This will likely involve dropping the testing of the radiation scheme with AERI data, for which Dr. Arnott was primarily responsible. The reason for this decision is due to the many uncertainties one encounters with field data, cloud dimensions, etc., making it unclear if an agreement between radiation transfer theory and field measurements is for the right reason. For instance, there is a factor of 3 uncertainty in ice particle mass alone, as determined from a measured size distribution. Remaining resources for this task will be used to reanalyze our laboratory measurements for hexagonal plates from the previous project, whereby FTIR measurements of extinction efficiency (Qext) were made in a cloud chamber (Mitchell et al. 2000a). Under these controlled conditions, measurement uncertainties were far lower than those associated with field measurements. It appears that our first analysis for plates can be improved through better estimates of the concentrations of undetected small crystals. As already described in two conference papers, comparisons of measured and predicted Qext test of our radiation scheme while at the same time they provide estimates of photon tunneling in columnar and planar ice crystals. We will also be intercomparing our radiation scheme with those from other groups.

2. Accomplishments to Date

A. Continued development of a GCM parameterization for mid-latitude cirrus size spectra

Prior to this project, we had analyzed 357 cirrus size distributions, or N(D), mostly from ARM IOPs. At this time, we have analyzed 682 additional N(D) from ARM IOPs, giving 1,039 total. A means of testing FSSP data for continuity with 2DC size spectra has been developed. This resulted in reducing the above total by only 7% (giving 966 N(D)). Testing for continuity has been recommended as a means for determining the validity of FSSP data (Gayet et al. 1996). Our N(D) parameterization scheme has been revised accordingly.

Our plans are to prepare a journal article on N(D) parameterization soon. A preprint article describing this scheme, for the International Conference on Clouds and Precipitation in Reno, Nevada, has been sent by mail.

B. GCM parameterization for tropical cirrus size spectra

We also have the beginnings of an N(D) parameterization for tropical cirrus, based on CEPEX and other data. We now have access to FSSP and 2DC data from the Kwajalein-TRMM experiment (KWAJEX), conducted in the western tropical Pacific, where sampling was generally near convection. Our long-term plans are to develop a tropical N(D) parameterization which accounts for radial distance from the convective column, based in part on KWAJEX and CEPEX data.

C. Submission of Paper to Journal of Atmospheric Sciences

A paper titled ‘Effective Diameter in Radiation Transfer: General Definition, Applications and Limitations’ has been submitted to the Journal of Atmospheric Sciences, and has been sent by overnight mail as part of this report. About half of the resources used to produce this paper came from this project, while the remainder came from the previous project. The main findings are:

A general definition of effective diameter, Deff, was derived from the concept of an effective photon path for any particle shape. This is the traditional definition for water clouds and is used by some groups regarding ice clouds:

$$\text{Deff} = 3\ \text{WC}/(2\ \text{rho}\ \text{P}),$$

where WC = water content (ice or water), P = N(D) projected area and rho = bulk density of ice or water.

Based on the work of Mitchell (2000), simple equations were formulated in terms of Deff, wavelength and refractive index, giving monochromatic coefficients for absorption and extinction, Babs and Bext, throughout the geometric optics, Mie and Rayleigh regimes. These expressions were tested against Mie theory, showing the limitations of the use of Deff as well as its usefulness.

For water clouds, the Deff expression for Babs appears accurate for any wavelength within 12%, and thus provides a simple means of treating terrestrial radiation in water clouds.

For ice clouds, the Deff expressions for Babs and Bext were not sufficiently accurate, due to much greater dispersion about the N(D) mean size relative to water clouds. The greater dispersion is due to the bimodal nature of the N(D), with absorption efficiencies, Qabs, being relatively low for the small crystal mode (D < 100 µm). Therefore numerical or analytical integration over the N(D) is needed for accurate values of Babs, since a single particle solution based on Deff will overestimate Qabs. The Deff expression for Bext suffered from exaggerated dependence on wave interference effects.

A new treatment of ice cloud radiative properties is offered, based on Mitchell (2000), giving analytical solutions for Babs and Bext in terms of ice crystal shape, bimodal N(D) parameters, wavelength and refractive index. Comparisons with Mie theory (using ice spheres) indicate accuracy within 10% for Babs, and within 10% for size parameter x > 1 for Bext, where x = 3.14 Deff /wavelength. This scheme was developed during the previous project, but is now submitted for publication.

Several schemes for predicting ice cloud radiative properties are founded on the assumption that the dependence of Babs and Bext on the size distribution can be described solely in terms of Deff and IWC. This assumption was tested by comparing the N(D) weighted efficiencies for absorption and extinction, Qabs and Qext, for three N(D) which have the same IWC and Deff, but for which N(D) shape differs, based on our analytical solutions for Babs and Bext, which explicitly treat N(D) shape. Uncertainties (percent differences) resulting only from N(D) shape differences can reach about 50% for Qabs and 65% for Qext in the thermal infrared. Also shown for the same conditions are Qabs and Qext predicted from a scheme based solely on Deff and IWC, over a wavelength range of 1 to 100 µm. The limitations of this approach are clear.

D. Funded Collaboration with Paul Stackhouse

During our previous project, Dr. Paul Stackhouse of NASA Langley Research Center was funded directly through DOE/ARM to help interpret our results through radiation transfer modeling, and is currently working with us on an unfunded collaborative basis in this project.

Paul’s work in the last and current project involved radiation transfer calculations in the thermal infrared (or TIR) to the test the broadband radiative effects of the new N(D) parameterization for tropical cirrus clouds. In particular, Dr. Stackhouse’s research:

- Examined the radiative impact of using a bimodal size spectrum in the thermal infrared (TIR) relative to an exponential distribution of particles. It was shown that for identical N(D) for D > 100 microns, the small mode of the bimodal N(D) produced emissivity differences up to 0.28 larger (63%) relative to exponential N(D). This maximum difference corresponds to a reduced outgoing LW radiative flux of 52 W m-2.

- Examined the relative importance of scattering in the TIR for tropical cirrus clouds, after the asymmetry parameter g was parameterized by the P.I. in the TIR from Dr. Ping Yang's calculations, based on the Finite Difference Time Domain and Improved Geometric Optics methods. In general, it was found that the zero scattering approximation yields fairly accurate emissivities (errors < 5%) and fluxes (errors < 8 W m-2) in the TIR, even for bimodal N(D).

E. Collaborations

1. Hadley Centre, U.K. Meteorological Office

- Dr. John Edwards has developed a means for diagnosing whether large scale cloud in the Unified Model (UM) GCM was of frontal or convective origin. This information is needed to apply our two N(D) parameterizations. Dr. Edwards has completed an initial set of one year simulations using our radiation and tropical + mid-latitude N(D) schemes, assuming planar polycrystals and asymmetry parameter (g) values corresponding to hexagonal columns. A comprehensive new microphysics scheme was also implemented (Wilson and Ballard 1999), which uses the ice particle fallspeed formula developed in Mitchell (1996).

- This new simulation was compared against a control integration based on our earlier work, described in Kristjansson et al. (2000), which assumes planar polycrystals and g values based on randomized fractals (Macke 1993). These g values are lower than for hexagonal columns. The new simulation shows improvements in the LW but errors increase in the SW, for both the tropics and mid-latitudes.

- The introduction of improved fallspeed relationships, and the dependence of ice mass sedimentation rates on the new N(D) parameterizations, resulted in higher ice sedimentation rates in the new simulation. This effect was greatest at mid-latitudes, since ice particle sizes at mid-latitudes are generally larger (with higher fallspeeds) than in the tropics. This in turn resulted in lower IWPs at mid-latitudes, which reduced zonal mean SW reflection on the order of 5 W m-2 in the mid-latitudes, with much smaller mean changes in the tropics. These changes in IWP had relatively little impact in the LW. Hence some of the above SW darkening at mid-latitudes was due to the new treatment of ice particle fallspeeds.\

- A provisional tuning of the new microphysics scheme was carried out, whereby more ice is produced at higher levels, with reductions in IWC lower down. Since mean size decreases with decreasing temperature, this results in greater SW reflection and decreased OLR. The tuning reduced SW errors in both the mid-latitudes and tropics, and further reduced LW errors in those regions, relative to the control simulation.

- The new scheme has further reduced the upper troposphere cold bias to a mere -1°C relative to the ECMWF reanalysis.

- There are many issues to be sorted out before some convergence can be made toward a new microphysics/radiation scheme for the UM. These results should be viewed as highly preliminary and just the beginning.

2. Scripps Institute

We are collaborating with Dr. Richard Sommerville's group at Scripps regarding their testing of our microphysical and radiation schemes in their SCM. The PI has discussed the above mentioned results with Richard over the phone, and has sent him a copy of our new paper. The PI hopes to visit Scripps this Fall, depending on what times are convenient to both parties.

3. NOAA's Geophysical Fluid Dynamics Laboratory

We are also collaborating with Dr. Leo Donner and his student, Matt Eisaman, in testing the new N(D) parameterizations and our radiation scheme in the GCM developed at the Geophysical Fluid Dynamics Laboratory. Thus far, much of this work has been centered on intercomparing our radiation code with that of Dr. Qiang Fu's code.

2. Impact on ARM Efforts

While it is uncertain what effect this work will have on ongoing efforts within ARM, it has the potential to influence ARM activities for the following reasons:

The paper submitted to J. Atmos. Sci. demonstrates that errors arising from neglect of N(D) shape effects can be far greater than errors associated with the application of electromagnetic theory to ice particle-radiation interactions. Schemes treating the single scattering properties of ice clouds, based solely on Deff and IWC, may contain implicit assumptions of N(D) shape. These assumptions need to be recognized and evaluated as new measurement technologies and advancements in our understanding of ice cloud microphysics become available.

Due to the dependence of absorption and extinction on N(D) bimodality, especially at terrestrial wavelengths, we recommend increased emphasis on characterizing the entire N(D) in ice clouds during ARM Cloud IOPs, especially for $D < 100$ µm. Jay Mace has also begun to address the importance of bimodal size spectra in cirrus. While the Lawson CPI instrument may have uncertainties regarding absolute concentration, comparing N(D) measured by the CPI with composite FSSP/2DC N(D) may lead to much lower uncertainties, and much improved characterization of the bimodal N(D) in ice clouds. Additional comparisons between the DRI Cloudscope and the FSSP during IOPs would also prove most valuable.

The use of Deff to parameterize ice cloud radiative properties in SCMs and GCMs may need to be reevaluated, especially when used in the TIR.

Satellite algorithms used to retrieve cloud properties (Deff, IWP, tau) may themselves be based on radiation schemes which use Deff to parameterize the single scattering properties. The properties retrieved may then depend on what N(D) were assumed in parameterizing the single scattering properties with Deff. This concern would apply primarily to wavelengths 3 µm and higher.

3. Publications

Since the first of the year, 3 conference papers were written (plus an ARM STM paper), but were primarily funded by the previous project. They are nonetheless referenced here, and sent through overnight mail, since it is recognized that ARM management may benefit by receiving them now rather than waiting another 5 months for the final report on the previous project (now under a no-cost extension). By the same reasoning, 3 journal articles funded under the last project have now been published, and reprints have been sent (2 copies of each). Previously, complete references were not available for these articles. They are now referenced below, along with the article just submitted to the Journal of the Atmospheric Sciences.

The paper 'Nighttime Retrieval of Ice Water Path' developed out of the work on effective diameter. It represents a novel method for estimating IWP at night via a 3.9 µm channel, contained on AVHRR, MODIS and other satellite sensors. Retrieved IWPs are less sensitive to ice particle size and shape relative to retrievals at solar wavelengths, and uncertainties are estimated at about ± 25%.

A. Journal Submission plus complete references for articles funded under previous project

Mitchell, D.L., 2000: Effective diameter in radiation transfer: General definition, applications and limitations. Submitted to *J. Atmos. Sci*. in July, 2000.

Mitchell, D.L., 2000: Parameterization of the Mie Extinction and Absorption Coefficients for Water Clouds. *J. Atmos. Sci*., 57, 1311-1326.

Kristjansson, J.E., J.M. Edwards, and D.L. Mitchell, 2000: Impact of a new scheme for optical properties of ice crystals on climates of two GCMs. *J. Geophys. Res*., 105, 10,063-10,079.

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Yang, P., K.N. Liou, K. Wyser and D.L. Mitchell, 2000: Parameterization of the scattering and absorption properties of individual ice crystals. *J. Geophys. Res*., 105, 4699-4718.

B. New Conference Papers (funded under previous project)

Ivanova, D., D.L. Mitchell, W.P. Arnott and M. Poellot, 2000: A GCM parameterization of bimodal size spectra for mid-latitude cirrus clouds. Preprints, 13th International Conference on Clouds and Precipitation, 14-18 August, Reno, Nevada.

Mitchell, D.L., D. Ivanova, A. Macke and G.M. McFarquhar, 2000: A GCM parameterization of bimodal size spectra for ice clouds. Proceedings of the Ninth ARM Science Team Meeting, March 22-26, 1999, San Antonio Texas.

Mitchell, D.L., W. P. Arnott and C. Schmitt, 2000: Photon tunneling contributions for laboratory grown hexagonal columns. Proceedings, 5th Conference on Electromagnetic and Light Scattering by Nonspherical Particles: Theory, Measurements, and Applications, AMS, August 28-September 1, 2000, Halifax, Nova Scotia, Canada.

Mitchell, D.L., and R.P. d'Entremont, 2000: Nighttime retrieval of ice water path. Proceedings, 5th Conference on Electromagnetic and Light Scattering by Nonspherical Particles: Theory, Measurements and Applications, AMS, August 28-September 1, 2000, Halifax, Nova Scotia, Canada.

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